International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)
ISSN(P): 2249-6890; ISSN(E): 2249-8001
Vol. 8, Issue 3, Jun 2018, 933-942

EXPERIMENTAL INVESTIGATION OF PERFORMANCE AND EMISSION CHARACTERISTICS OF AN IDI DIESEL ENGINE USING HOMOGENIZED WATER IN DIESEL EMULSION

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ABSTRACT

A comparative experimental study on a 1.8L IDI diesel engine has been carried out to evaluate the influence of homogenized water in diesel emulsion on performance and exhaust emissions against base fuel diesel. The emulsions tested were diesel fuels by 5%, 10% and 20% by volume of water. Experiments were conducted at full load condition and during testing; the engine speed was maintained in the range of 1000 to 4000 rpm and varied in steps of 500 rpm. Emission parameters NOx, CO, were measured. Reduction in exhaust temperature and smoke opacity was observed with all the tested emulsions. Contradictorily, NO_X was found to be increasing with increase in water content which might be an outcome of a very weak or absence of the microexplosion phenomenon. Power was reduced, while specific fuel consumption of water in diesel emulsions was found to be higher than diesel.

KEYWORDS: Water in Diesel Emulsion (WiDE), Exhaust Emission, Engine Performance, Microexplosion & Droplet

Original Article

Received: Apr 12, 2018; **Accepted:** May 23, 2018; **Published:** Jun 13, 2018; **Paper Id.:** IJMPERDJUN201899

INTRODUCTION

Diesel engines are preferred over the gasoline engines because of their robustness, fuel economy and high power output either in automobiles or in industrial applications. On the other hand it is considered as a major polluting source like particulate matter (PM) and Nitrogen Oxides (NO_X) Researchers reported that water in diesel emulsion (WiDE) has been proven to be a promising alternative fuel to reduce the diesel engine exhaust emission. Out of several methods available for the introduction of water into the combustion chamber, water encapsulated in the diesel with the presence of surfactant or emulsifier has been widely accepted practice since it does not require any engine modification. It has been found that when WiDE is used as fuel, the decrease in the temperature of the combustion products causes the reduction in NOx. Also the presence of water during the intensive formation of soot particles seems to reduce the rate of formation of soot particles. The concept of microexplosion phenomenon is often referred as the reason behind exhaust emission reductions. Microexplosion is accomplished due to the difference in the volatility between the water and diesel. Water reaches the superheated state much earlier than diesel which in turn leads to secondary atomization results in better air-fuel mixture hence better combustion is achieved. WiDE is capable of overcoming the traditional tradeoff by reducing both NOx and PM simultaneously [1, 2]. Outcome of various studies on WiDE as fuel claimed that NOx has been reduced. When WiDE was tested

on multi-cylinder industrial diesel engine, a maximum of 37% reduction in NOx has been reported under steady-state operation [3]. Another study with a single cylinder diesel engine claimed that 10% NOx reduction has been achieved with 10% water content and 25% reduction with WiDE containing 20% water [4]. With a lower injection pressure, NOx was reduced between 30-50% and the same has increased up to 24% with higher injection pressure with same 4 cylinder, HSDI diesel engine [5]. Park et al. [6] reported that 11.6% reduction in NOx was achieved when tested on 6 cylinder TCI diesel engine. 18-20% NOx reduction has been reported by Samec et al. [7] with water content of 10 to 15%. With a 6% water content WiDE, an 24% reduction in NOx was reported [8]. Many other experimental studies under different testing conditions also indicated that achievable NOx reductions [9-12]. As for PM, at low load engine testing conditions an reduction of 94% were reported [5] and approximately 34% PM reductions were achieved [6]. Barnaud et al. [9] and Matheaus et al. [10] reported a drop of 16% and 50% on PM exhaust in their separate studies. Considerable PM reductions has been reported by other researchers as well [13-15].

As a penalty, the engine power and torque were found to be slightly decreased when using WiDE as fuel to achieve the emission reduction [1, 3, 15, 16]. This reduction is attributed to the presence of water which does not possess any calorific value. But, improved engine efficiency has been reported by [14]. Abu Zaid and coworkers [17] observed an increase in engine torque and power as the water content in WiDE increases. Also, an increase in brake thermal efficiency for WiDE with 20% water has been reported from other studies [1, 3, 13, 17]. On the other hand, most of the researchers reported that specific fuel consumption (SFC) was on the increased when compared to diesel for the same power output [1, 13]. An increase of 22-26% in SFC was mentioned [5] while Nadeem et al. [15] reported a 15% hike of SFC and 26% increase in SFC has been reported by [3]. Despite different engine setups and testing methodologies, there was a common agreement that simultaneous reduction of NOx and PM is achievable with WiDE as fuel.

Previous studies on WiDE in diesel engine combustion, in which the preparation of emulsions are limited to any one of the following base fuel (i. e) neat diesel, low-grade diesel or Ultra-low sulfur diesel (ULSD). Whereas in the present study the emulsions were prepared using a base fuel which contains 95% diesel and 5% palm oil methyl ester. The present experimental work aims to ascertain the effect of homogenized water in diesel emulsion (WiDE) with three different percentages of water content i. e 5, 10 and 20% on engine performance and exhaust emissions. The testing was carried at full load condition for seven different speeds. The exhaust gas emissions such as NOx, CO, and smoke opacity were measured and analyzed in addition to the engine power and bsfc.

MATERIALS AND METHODS

Emulsion Preparation and Characterization

Three blends of homogenized water in diesel emulsions (WiDE) used for this experiment were prepared and supplied by SIT Schiffs & Industrie Technik (M) Sdn Bhd, Malaysia. The emulsion was stabilized with 2% blend of commercially available surfactants. B5 diesel was used to prepare the emulsion which contains 95% diesel and 5% palm oil methyl ester. The water droplets were examined using a digital microscope and was found to be uniformly distributed and in order of size less than 2μm. The WiDE was considered stable when there was no observable separation for a period of 336 hours. Physical properties of diesel and tested emulsions are tabulated in Table 1.

Table 1: Physical Properties of Wide Samples

Sample	Density @20°C (kg/m^3)	Viscosity @ 40°C (mm²/s)	GCV (J/g)	Nitrogen %(w/w)	Carbon % (w/w)
Diesel	842.9	3.4091	42600	0.1013	81.38
WiDE-5	849.76	5.7925	37460	0.1123	80.32
WiDE-10	854.44	6.1463	36942	0.193	78.65
WiDE-20	870.17	7.969	32481	0.221	68.94

The experiments were performed on a FORD XLD 418 IDI engine. Separate tanks were used to store the diesel and emulsions. There were no modifications made on either engine or injection pump setting. The engine was coupled with an eddy current dynamometer rated at 150 kW between 2800 and 8000 rpm and a maximum torque rating of 500 Nm. Autotest IV engine control unit was used to control and for data management. In addition, Autochek exhaust gas analyzer capable of measuring NOx, and CO were used to measure the combustion exhaust gases. A smoke opacity meter combined with the analyzer with an accurate scale range of +/- 2% were employed to measure the exhaust smoke.

Experimental Procedure

Experiments were conducted at full load condition at seven different speeds starting from 1000 rpm to 4000 rpm at an interval of 500 rpm. Initial warm-up of the engine was done using diesel and later switched to WiDE. Each speed was maintained until all readings were stabilized before the required data were recorded. Exhaust emissions and smoke opacity were measured simultaneously.

RESULTS AND DISCUSSIONS

EFFECT OF WIDE ON ENGINE PERFORMANCE

Engine Power

The powers produced by all the emulsions were found to be lesser than diesel for all engine speeds. However, the difference in power was small up to the engine speed of 2000 rpm and from this speed on it was found that the differences to be increasing as shown in Figure 1. The power produced by the emulsions compared to diesel was decreasing with increasing water content in WiDE. Generally it is observed that the power increases with the increasing engine speed up to a speed of 2000 rpm progressed further with a slight drop.

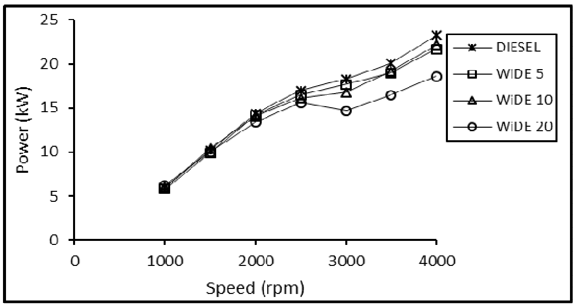

Figure 1: Engine Power Output Vs Speed for Diesel and WiDE

The maximum power reduction with WiDE-5 was 6.4% which is fairly in agreement with results obtained by [13] when emulsion with 5% water was tested on a 4-cylinder DI engine. For WiDE-10 the power reduction was found to be 8% which is similar to the findings of Barnes et al. [18] that for 10% water content by volume resulted in a power loss of 7-8%. In case of WiDE-20, a maximum of 19.8% loss in power was observed. Again, WiDE-20 showed the lowest power at all the speeds.

Brake Specific Fuel Consumption (BSFC)

The relationship between specific fuel consumption and the speed of the diesel and WiDE are plotted in Figure 2. The bsfc is decreased initially, then increased with engine speed is increased. This is due to the fact that at the lower speed the heat transfer to the cylinder wall and the frictional losses consume more fuel for the same output. bsfc for the baseline fuel was found to lesser for all the speeds. The graph shows the trend for fuel consumption, which is similar to all emulsions except for WiDE-20. Specific fuel consumption for the WiDE is higher because of its lower calorific value and higher density compared to base fuel. The reduction in the calorific value of the WiDE is due to the fact that the amount of diesel in the emulsion is reduced to match the amount of water content in the WiDE. Hence, more fuel is desired to maintain the speed of the given load. A similar trend of increase in BFSC has been reported by other researchers [1, 13, 19-21].

As shown in Table 1, the calorific value of the emulsions was found to decrease with an increase in water content.

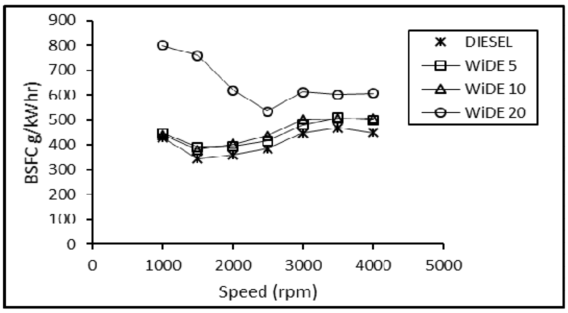

Figure 2: BSFC Vs Speed For Diesel and WiDE

The difference in calorific value among WiDE-5 and WiDE-10 was about 518 J/g and the difference was about 4461 J/g for WiDE-10 and WiDE-20. These differences in heating value can be perceived from Figure 2, it is also observed that the BSFC for WiDE-5 and WiDE-10 are close to each other since the difference among these emulsions were small. Among the tested emulsions WiDE-20 recorded the highest fuel consumption because of its lowest calorific value among the other emulsions. Diesel, WiDE-5, and WiDE-10 had minimum fuel consumption at 1500 rpm and the maximum of 3500 rpm. Whereas for WiDE-20 lowest SFC was at 2500 rpm.

Exhaust Gas Temperature

The relationship between the exhaust gas temperature and the engine speed at full load condition is plotted in Figure 3. It is obvious that the exhaust temperature for all WiDE was found to be less, based on the water content which results from the condensation of water vapor in the engine exhaust.

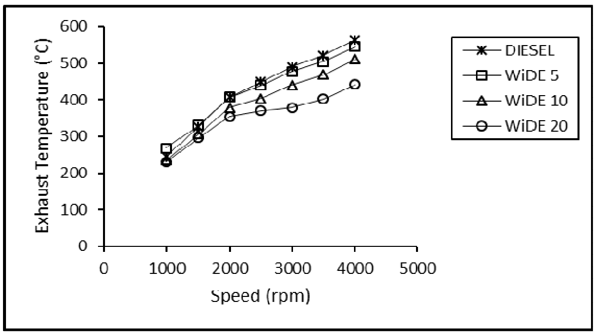

Figure 3: Exhaust Gas Temperature Vs Speed for Diesel and WiDE

As shown in Figure 3, increase in water in WiDE proportionately reduces the exhaust temperature Similar, trends were reported by [17] when 5-20% water content in WiDE was tested on a single cylinder diesel engine. Diesel produced the higher exhaust temperature for all speeds. At the maximum speed and full load condition the exhaust temperature reduction for WiDE-5, WiDE-10 and WiDE-20 were 3.36%, 9.39%, and 21.63% respectively.

EFFECTS OF WIDE ON ENGINE EXHAUST EMISSIONS

Carbon Monoxide Emission (CO)

Figure 4 depicts the CO emission of diesel and WiDE at full load for various speed. CO of WiDE-5 and 10 was higher than diesel and WiDE-20 was lower than the diesel at speed of 1000 rpm. Then drops to insignificant difference level at 1500 rpm and started to rise with speed. As shown in Figure 4 all the tested fuels follow the same trend.

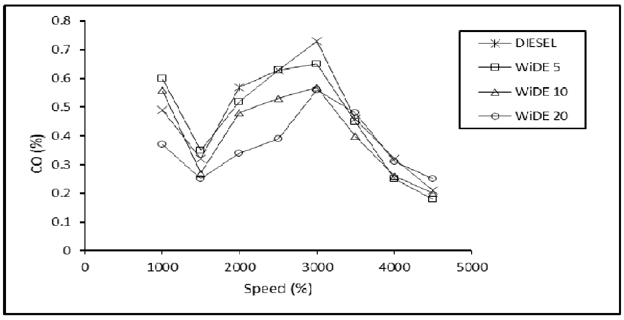

Figure 4: CO Emissions for Diesel and WiDE

The probable reason for increasing CO trend is due to the lower combustion temperature at lower speeds [16, 22] as the speed increases and at higher combustion temperatures the CO tends to decrease. [23] states that the oxidation of CO into CO_2 is not possible when the temperature is lower than 1400 K. From the CO emission graph, diesel has the highest CO when compared to WiDE. This clearly shows that WiDE has better air-fuel mixture [24]. On the other hand, it is clear that the oxygenating rate for WiDE is higher to convert CO to CO_2 compared to diesel resulting from the better combustion but the higher temperature of WiDE inside the combustion chamber is potentially due to the weaker microexplosion of very smaller droplets size.

Nitrogen Oxide Emission (NOx)

The NOx formation is mainly due to in-cylinder temperature, ignition delay, excess oxygen and nitrogen from the burning fuel [25]. The changes in NOx emissions are plotted against engine speed for both diesel and WiDE are shown in Figure 5. For the speed range from 1500 rpm to 2000 rpm there was no prominent difference between diesel and WiDE, but as the speed increases, NOx showed an increasing trend.

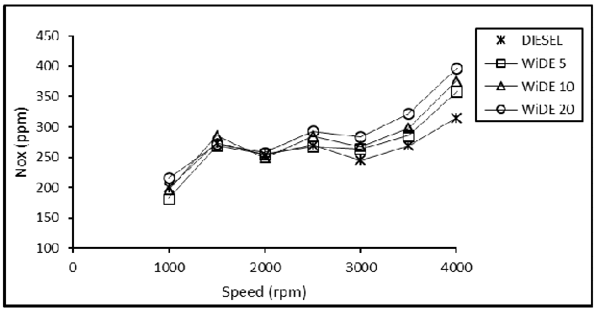

Figure 5: Nox Emissions for Diesel and WiDE

But, the majority of researchers claimed when WiDE used as fuel it reduces peak flame temperature. According to [1], the presence of water in WiDE absorbs the heat in the form of latent and sensible heat which reduces the combustion temperature in that way inhibiting NOx formation. However, in this study, the NOx produced is increasing with the increase in the water content is due to the fact that the microexplosion is not intensive or too weak. The excessive oxygen present in the chemical structure of emulsion contributes to the higher NOx. In addition to the excess oxygen, the trend also shows that as the engine speed increases the rise in temperature contributes to the increase in NOx. The homogenized WiDE used in this study has uniformly distributed droplet size of 1-2µm, smaller the droplets lead to better combustion [26].

Adversely, too smaller droplet size would have resulted in an enhanced combustion, rapid collective evaporation, with less intensive microexplosion and the heat sink effect of the water presence was not achieved to its fullest extent resulting in higher combustion temperature. On the other WiDE studies on a four-cylinder diesel engine by [26] claimed that smaller droplet size of 2.1 µm produced by ultrasonic emulsification had slightly higher NO emissions compared to a droplet size of 2.6 µm produced by mechanically homogenized. This endorses that even a small difference of 0.5 µm droplet diameter had an influence on NOx emissions.

According to Huo et al. [27] on the WiDE spray study at elevated temperature and pressure in a constant volume chamber, claims that at lower injection pressure around 70 MPa and higher ambient temperature favors the occurrence of puffing and disruptive droplet combustion. Whereas in the present study the injection pressure is only 11.8 MPa. Separate studies on single droplet using combustion chamber by [28] and [29] affirms that the smaller droplet size has the low tendency for microexplosion.

NOx showed an increasing trend with the increasing speed, which could be resulted only from the increasing combustion temperature. According to [21], an increase in NO was observed due to increased combustion temperature and oxygen availability, when WiDE was tested on a single cylinder DI diesel engine at a constant speed of 1500 rpm. The high amount of premixed combustion phase resulted from the ignition delay [23] when WiDE is used as fuel when these burning WiDE blends with the fresh intake of fuel combust during this phase could have resulted in high heat release. At the maximum speed of 4000 rpm the NOx for WiDE-20, WiDE-10 and WiDE-5 were 20.65%, 16.22%, and 12.01% higher the baseline diesel.

Smoke Opacity of WiDE and Diesel

The smoke opacity of WiDE and diesel are plotted in Figure 6. Smoke opacity for all the fuels appeared to decrease with engine speed at same constant full load condition. The declining trend is due to the fact that torque was reducing with increasing engine speed. The combustion of diesel produced the highest smoke, whereas the WiDE has emitted lesser smoke. The formation of black smoke largely resulted from the incomplete combustion, comparatively the combustion was improved with an increase in speed which is more significant in case of WiDE. The presence of water increases the ignition delay which resulted in better air-fuel mixing which leads to improved combustion. In addition, more smoke reduction with WiDE is due to high oxygen content which increases the flame speed during the air-fuel interactions [30].

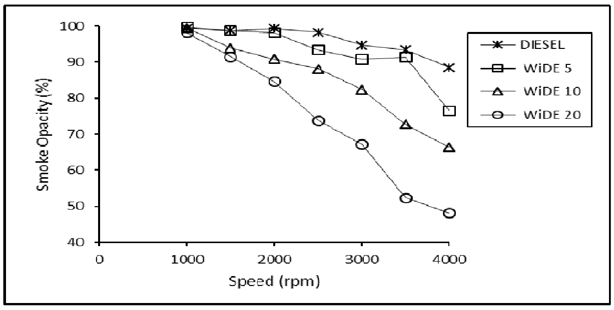

Figure 6: Smoke Opacity for Diesel and WiDE

At lower engine speed the difference in smoke opacity among diesel and the emulsion was lesser and WiDE-5 produced less significant differences in the smoke compared to diesel at all speeds. Whereas, WiDE-10 and WiDE-20 reduced the black smoke to a greater extent. At 3000 rpm the smoke opacity was 13.6%, 25.06% and 45.7% lesser than diesel for WiDE-5, WiDE-10 and WiDE-20 respectively.

CONCLUSIONS

Homogenized water in diesel emulsion (WiDE) with 5%, 10% and 20% of water content was tested on an IDI diesel engine without any modification. It must be noted that exhaust emission reductions depend on the type of engine, its age, modifications made on engine settings and mode of operating cycle. By changing engine parameters like injection time and pressure, monitoring the heat release rate and in-cylinder pressure would give better diagnostics of in-depth combustion analysis so as to achieve optimum usage of WiDE. The important effect of WiDE limited to the present test conditions on the engine performance and emissions is summarized as follows.

The presence of water in WiDE leads to a loss of power of the engine compared to base fuel. Brake Specific fuel consumption was found in higher in case of WiDE compared to base fuel. Exhaust temperature was reduced with WiDE than base fuel. Smoke opacity was reduced to a greater extent with WiDE, which is almost proportionate to the percentage of water content. Contradictorily, increase in NOx was observed to increase in water content of WiDE which questions the uncertainty of microexplosion phenomenon of homogenized emulsions inside the combustion chamber. WiDE 10 and WiDE 20 has lesser CO when compared with base fuel.

ACKNOWLEDGEMENT

The authors thank Universiti Teknologi PETRONAS for the financial and facility support for the study. Schiffs & Industrie Technik (M) Sdn Bhd, is also highly acknowledged for preparing and providing the homogenized WiDE samples. The authors would like to express their gratitude to Ahmad Shahrul Bin Ahmad and Hazirah Jamaluddin for their assistance in conducting the experiments.

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